Supersymmetric Lepton Flavor Violation

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Abstract. We study a new supersymmetric mechanism for lepton flavor violation in a minimal extension of the MSSM with low-mass heavy singlet neutrinos, which is fully independent of the flavour structure of the soft SUSY breaking sector. We find that $\ell \to \ell' \gamma$ processes are forbidden in the SUSY limit, whilst the processes $\ell \to \ell' \ell_1 \ell_2$ and $\mu \to e$ conversion in nuclei can be enhanced well above the observable level, via large neutrino Yukawa-coupling effects.

Keywords: neutrino, low-scale seesaw, lepton flavor violation, supersymmetry
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We present a new mechanism of lepton flavor violation (LFV) in supersymmetric theories [1]. The mechanism is independent of the flavour structure of soft SUSY breaking sector and its origin is fully supersymmetric. Therefore, we call this mechanism supersymmetric LFV (SLFV). To illustrate the details of SLFV, let us assume an R-parity conserving seesaw extension of the MSSM with one singlet heavy neutrino per generation (MSSM3N). The leptonic part of the MSSM3N is given by

$$W_{\rm lepton} \;=\; \widehat{E}^C \mathbf{h}_e \widehat{H}_d \widehat{L} + \widehat{N}^C \mathbf{h}_\nu \widehat{L} \widehat{H}_u + \widehat{N}^C \mathbf{m}_M \widehat{N}^C \,. \qquad (1)$$

Here $\widehat{H}_{u,d}$, $\widehat{L}$, $\widehat{E}$ and $\widehat{N}^C$ denote the two Higgs-doublet superfields, the three left- and right-handed charged-lepton superfields and the three right-handed neutrino superfields, respectively. The Yukawa matrices, $\mathbf{h}_{\nu,e}$ and Majorana mass matrix $\mathbf{m}_M$ are complex 3-by-3 matrices. In a minimal supergravity (mSUGRA) approach to MSSM3N, the soft SUSY breaking usually satisfies universal conditions at GUT scale. Moreover, singlet neutrino masses are two to four orders of magnitude below the GUT scale to account for the observable light neutrinos via the usual sessaw mechanism. In this case, the heavy neutrino LFV contributions are suppressed by a factor m_ν/M_N, with $m_\nu \lesssim 0.1$ eV [2], and LFV can induced only sizeably through radiatively induced off-diagonal SUSY breaking parameters, such as $\widetilde{\mathbf{M}}^2_{L,E}$ and $\mathbf{A}_e$ [3, 4]. This soft-SUSY breaking mechanism represents the standard paradigm for LFV in SUSY models.

In stark contrast to soft LFV [3, 4], in supersymmetric models with low-scale singlet neutrinos, a different source of LFV can become dominant which originates from large neutrino Yukawa-coupling effects [1]. This can naturally take place in low-scale seesaw models [5, 6, 7, 8], where the smallness of the light neutrino masses is accounted for by quantum-mechanically stable cancellations [8] due to the presence of approximate lepton flavor symmetries [8, 9], implying the existence of nearly degenerate heavy Majorana neutrinos ($\mathbf{m}_M \approx m_N \mathbf{1}$). These approximate flavour symmetries allow the Majorana mass scale m_N to be as low as 100 GeV. In these models, LFV transitions

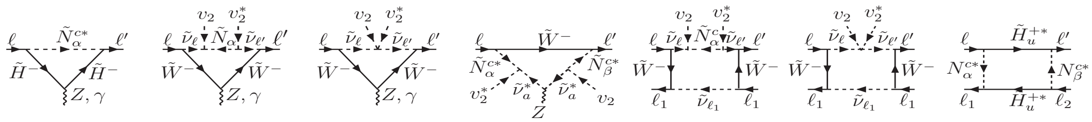

FIGURE 1. Feynman graphs giving rise to leading SLFV effects in the lowest order of an expansion in v_u and m_N^{-1}. Not shown are diagrams obtained by replacing the tilted SUSY states $\widetilde{H}_u^-$, $\widetilde{W}^-$, $\widetilde{N}_\alpha$ and $\tilde{\nu}_l$ with their untilted counterparts.

from a charged lepton $l = e,\, \mu,\, \tau$ to another $l' \neq l$ are enhanced by the ratios [10, 11, 12]

$$\Omega_{\ell\ell'} \;=\; \frac{v_u^2}{2m_N^2}\,(\mathbf{h}_\nu^\dagger \mathbf{h}_\nu)_{ll'} \tag{2}$$

and are not constrained by the usual seesaw relation m_ν/m_N, where $v_u/\sqrt{2} \equiv \langle H_u \rangle$ is the vacuum expectation value (VEV) of the Higgs doublet H_u, with $\tan\beta \equiv \langle H_u \rangle / \langle H_d \rangle$.

To assess the significance of SLFV, we assume that the soft SUSY-breaking scale $M_{SUSY} \ll m_N$, the superpotential $\widehat{H}_u\widehat{H}_d$-mixing parameter $\mu \ll m_N$, and that $\widetilde{\mathbf{M}}^2_{L,E}$ and $\mathbf{A}_e$ are flavor conserving, e.g. proportional to $\mathbf{1}$ at the energy-scale m_N.

Within the above framework, we calculate the leading SLFV amplitudes close to the SUSY limit in the lowest order of v_u and m_N^{-1}. The leading order diagrams in g_W and $\mathbf{h}_\nu$ are given in Fig. 1. In a self-explanatory notation, the pertinent LFV amplitudes read

$$\begin{aligned}
\mathscr{T}_\mu^{\gamma l' l} &= \frac{e\,\alpha_w}{8\pi M_W^2}\,\bar{l'}\Big(F_\gamma^{l'l}\,q^2\gamma_\mu P_L + G_\gamma^{l'l}\,i\sigma_{\mu\nu}q^\nu m_l P_R\Big)\,l\;,\\
\mathscr{T}_\mu^{Z l' l} &= \frac{g_w\,\alpha_w}{8\pi\cos\theta_w}\,F_Z^{l'l}\,\bar{l'}\gamma_\mu P_L l\;,\\
\mathscr{T}_l^{l' l_1 l_2} &= -\frac{\alpha_w^2}{4M_W^2}\,F_{\rm box}^{ll' l_1 l_2}\,\bar{l'}\gamma_\mu P_L l\;\bar{l_1}\gamma^\mu P_L l_2\;,
\end{aligned} \tag{3}$$

and $q = p_{\ell'} - p_\ell$. The amplitudes $\mathscr{T}_l^{l' u_1 u_2}$ and $\mathscr{T}_l^{l' d_1 d_2}$ have the same structure as amplitude $\mathscr{T}_l^{l' l_1 l_2}$ up to replacements $\ell_i \to u_i \to d_i,\; i = 1,2$. The form factors $F_\gamma^{l'l}$, $G_\gamma^{l'l}$, $F_Z^{l'l}$, $F_{\rm box}^{ll' l_1 l_2}$, $F_{\rm box}^{ll' u_1 u_2}$ and $F_{\rm box}^{ll' d_1 d_2}$ receive contributions from both the heavy neutrinos $N_{1,2,3}$ and the right-handed sneutrinos $\widetilde{N}_{1,2,3}$. To illustrate SLFV effects we give explicit form of the form factors $F_\gamma^{l'l}$, $G_\gamma^{l'l}$ and $F_Z^{l'l}$ in the Feynman gauge,

$$(F_\gamma^{l'l})^N = \frac{\Omega_{\ell\ell'}}{6s_\beta^2}\ln\frac{m_N^2}{M_W^2}\;, \qquad (F_\gamma^{l'l})^{\widetilde{N}} = \frac{\Omega_{\ell\ell'}}{3s_\beta^2}\ln\frac{m_N^2}{\widetilde{m}_h^2}\;, \tag{4}$$

$$(G_\gamma^{l'l})^N = -\Omega_{\ell\ell'}\left(\frac{1}{3s_\beta^2} + \frac{1}{6}\right), \qquad (G_\gamma^{l'l})^{\widetilde{N}} = \Omega_{\ell\ell'}\left(\frac{1}{3s_\beta^2} + \frac{M_W^2}{6\widetilde{m}_1^2}\right), \tag{5}$$

$$(F_Z^{l'l})^N = -\frac{3\,\Omega_{\ell\ell'}}{2}\ln\frac{m_N^2}{M_W^2} - \frac{(\Omega_{\ell\ell'}^2)}{2s_\beta^2}\,\frac{m_N^2}{M_W^2}\;, \quad (F_Z^{l'l})^{\widetilde{N}} = \frac{\Omega_{\ell\ell'}}{2}\ln\frac{m_N^2}{\widetilde{m}_1^2} + \frac{(\Omega_{\ell\ell'}^2)_{l'l}}{4s_\beta^2}\,\frac{m_N^2}{M_W^2}\,\ln\frac{m_N^2}{\widetilde{m}_2^2}\;. \tag{6}$$

The form factors $F_{\rm box}^{ll' l_1 l_2}$, $F_{\rm box}^{ll' u_1 u_2}$ and $F_{\rm box}^{ll' d_1 d_2}$, and masses $\widetilde{m}_h^2$, $\widetilde{m}_1^2$ and $\widetilde{m}_2^2$ are given in [1]. Note that in the SUSY limit $\tan\beta \to 1$, $\mu \to 0$ and $\widetilde{m}_h^2, \widetilde{m}_1^2, \widetilde{m}_2^2 \;\to\; M_W^2$.

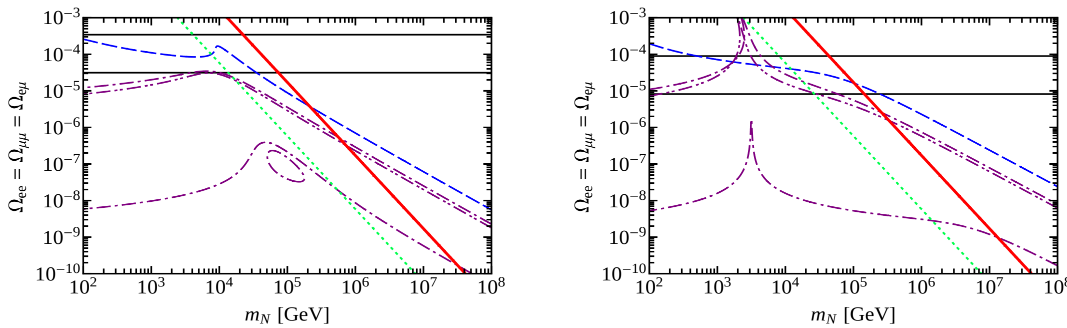

FIGURE 2. Exclusion contours of $\Omega_{e\mu}$ versus m_N for $\Omega_{\ell\ell'}$ values defined in the text. The contour lines are defined by experimental limits and future sensitivities: $B(\mu^- \to e^-\gamma) < 1.2\times 10^{-11}$ [15] (upper horizontal line), $B(\mu^- \to e^-\gamma) \sim 10^{-13}$ [16] (lower horizontal line), $B(\mu^- \to e^-e^-e^+) < 10^{-12}$ [15] (dashed line). We also include constraints from the non-observation of $\mu \to e$ conversion in $^{48}_{22}$Ti and $^{197}_{79}$Au, $R^{\rm Ti}_{\mu e} < 4.3\times 10^{-12}$ [17] (dash-dotted) and $R^{\rm Au}_{\mu e} < 7\times 10^{-13}$ [18] (dash-double-dotted), as well as potential limits from a future sensitivity to $R^{\rm Ti}_{\mu e}$ at the 10^{-18} level [19] (lower dash-dotted line). Left panel represents SLFV results. In the right panel the quantum effects due to $\widetilde{N}_{1,2,3}$ are ignored.

Notice that the photonic dipole form factor $G^{l'l}_\gamma = (G^{l'l}_\gamma)^N + (G^{l'l}_\gamma)^{\widetilde{N}}$ vanishes in the SUSY limit, while beyond the SUSY limit it strongly depends on the SUSY breaking sector. That is a consequence of the SUSY non-renormalization theorem [13].

In all other form factors, but $F^{l'l}_Z$, N and $\widetilde{N}$ contributions add constructively. Although in $F^{l'l}_Z$ N and $\widetilde{N}$ contributions add destructively, $F^{l'l}_Z$ is strongly enhanced in the large m_N limit by the logarithmic factor in $\widetilde{N}$ contribution. The m_N limit corresponds to the large neutrino Yukawa couplings $\mathbf{h}_\nu$ (see Eq. (2)), and in that limit the Ω^2 terms dominate in Z and leptonic box amplitudes.

We now present predictions for the LFV observables: $\ell \to \ell\gamma$ [11], the lepton number conserving processes $\ell \to \ell'\ell_1\ell_2$ [11], and the rate $R_{\mu e}$ for $\mu \to e$ conversion in nuclei [14, 1]. We fix $\mu = \widetilde{M}_Q = M_{\tilde{\nu}} = 200$ GeV, $M_{\widetilde{W}} = 100$ GeV and $\tan\beta = 3$. The impact of SLFV on $\mu \to e$ and $\tau \to e$ is presented in Figs. 2 and 3 respectively. The diagonal dotted lines indicate the regime where terms $\propto (\Omega_{\ell\ell'})^2$ dominate the LFV observables, whilst the area above the diagonal solid lines represent a non-perturbative regime with $\mathrm{Tr}\,(\mathbf{h}^\dagger_\nu \mathbf{h}_\nu) > 4\pi$, which limits the validity of our predictions. The areas above or within contours are exluded.

Limits from the absence of $\mu \to e$ transitions are presented in Fig. 2. We assume a scenario with $\Omega_{ee} = \Omega_{\mu e} = \Omega_{\mu\mu}$ and $\Omega_{\tau i} = 0$, $i = e, \mu, \tau$ [20]. Fig. 2 shows the impact of SLFV on $\mu \to e$ decays. $B(\mu \to e\gamma)$ leads to weaker $\Omega_{\mu e}$ constraints than non-SUSY case and gives no useful information for low-scale SUSY seesaw scenario. $B(\mu \to eee)$ and $R_{\mu e}$ give much stronger constraints on $\Omega_{\mu e}$ in SLFV than in non-SUSY case. $R_{\mu e}$ still gives the best constraints for all m_N values except for $m_N \sim 3$ GeV. The projected PRISM experimental limit $R^{\rm Ti}_{\mu e} \sim 10^{-18}$ [19] at $m_N \sim 10^8$ GeV reaches the sensitivities of order $\Omega_{\mu e} \sim 10^{-10}$.

Limits from the non-observation of $\tau \to e$ transitions are presented in Fig 3, assuming $\Omega_{ee} = \Omega_{\tau e} = \Omega_{\tau\tau}$ and $\Omega_{\mu i} = 0$, $i = e, \mu, \tau$. Given the constraints [20], a positive signal for

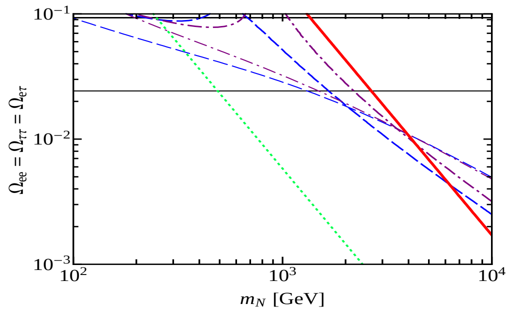

FIGURE 3. Exclusion contours of $\Omega_{e\tau}$ versus m_N for $\Omega_{\ell\ell'}$ values defined in the text. The limits are similar for a complementary scenario with e replaced by μ. SLFV limits and non-SUSY limits on $\Omega_{\tau e}$ are represented by thicker and thiner lines respectively. We use the experimental upper limits [15] on $B(\tau^- \to e^-\gamma) < 1.1\times10^{-7}$ (solid lines), $B(\tau^- \to e^-e^-e^+) < 3.6\times10^{-8}$ (dashed lines) and $B(\tau^- \to e^-\mu^-\mu^+) < 3.7\times10^{-8}$ (dash-dotted lines).

$B(\tau^- \to e^-e^-e^+)$ close to the present upper bound would signify that SLFV originates from rather large Yukawa couplings and $m_N \gtrsim 3$ TeV.

In summary, we have shown that low-mass right-handed sneutrinos can sizeably contribute to observables of LFV. Thanks to SUSY, they can significantly screen the respective effect of the heavy neutrinos on the photonic μ and τ decays. Hence SLFV can be probed more effectively in present and future experiments of $\mu \to e$ conversion in nuclei. The 3-body decay observables, such as $\mu \to eee$ and $\tau \to eee$, provide valuable complementary information on LFV. In particular, the former eliminates a kinematic region that remains unprobed in the non-SUSY case by $\mu \to e$ conversion experiments.

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